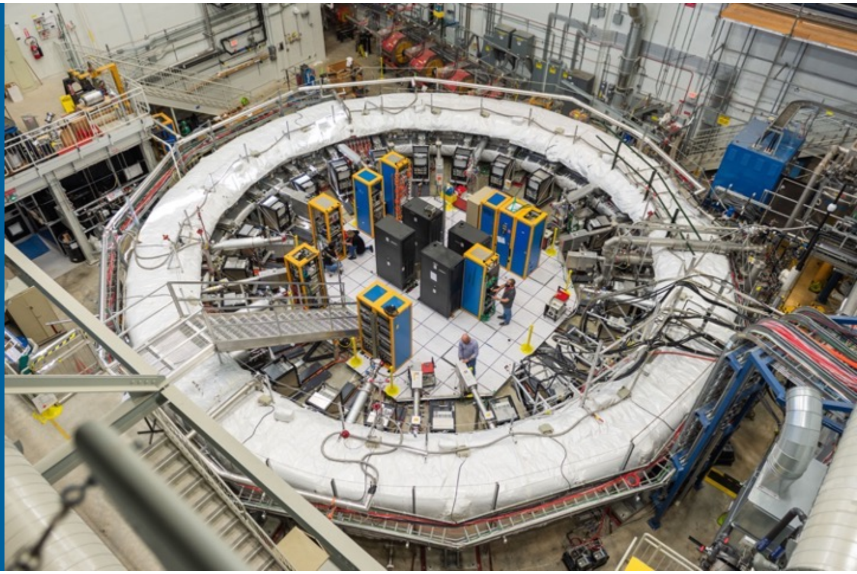
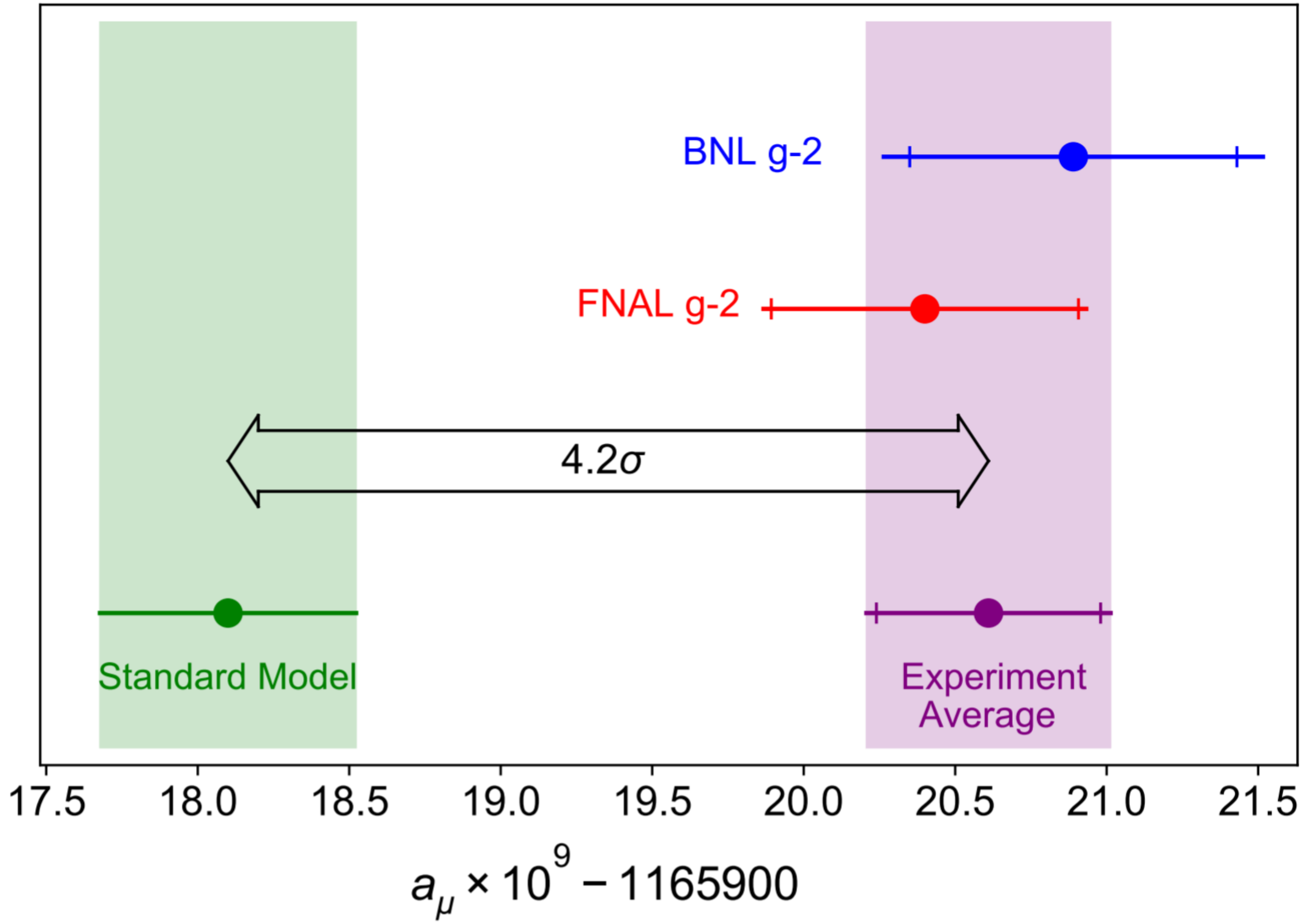
NEW RESULT FROM THE MUON g-2 EXPERIMENT AT FERMILAB



PETER WINTER
Muon g-2 Co-Spokesperson

Intensity Frontier Group Leader
High Energy Physics Division
Argonne National Laboratory

MUON g-2 TWO YEARS AGO IN 2021



$$a_\mu(\mathrm{FNAL}) = 116\,592\,040(54) \times 10^{-11} \quad (0.46\,\mathrm{ppm})$$
$$a_\mu(\mathrm{Exp}) = 116\,592\,061(41) \times 10^{-11} \quad (0.35\,\mathrm{ppm})$$

OUTLINE

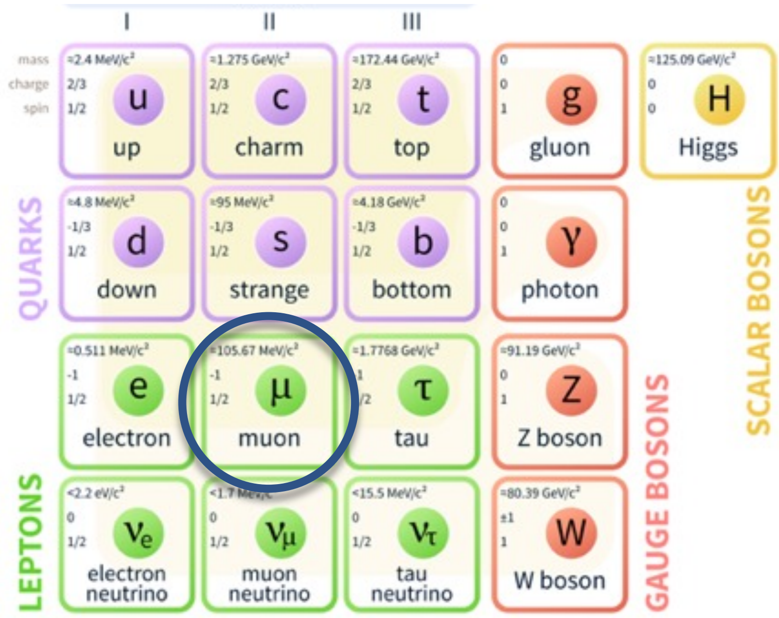
- Who am I?
- Short intro to Muon g-2
- My path to the ECA and lessons learned
- Muon g-2: Status and outlook
- Rare Processes and Precision Frontier: A personal view

WHO AM I?

- Studied physics at the university of Bonn, Germany
- PhD at Research Center of Jülich, Germany
- PostDoc on muon precision experiments (MuLan, MuCap, MuSun @ PSI):
  - 2005-2010: University of Illinois at Champaign-Urbana
  - 2010-2012: University of Washington
- ANL staff scientist since 2012 with research focus on Muon g-2:
  - Intensity Frontier Group Leader since 2019
  - Collaboration member of Muon g-2, mu2e, and DUNE

SHORT INTRO TO MUON g-2

SETTING THE SCENES FOR MUON g-2



- 2^{nd} **generation** elementary particle
- Big cousin of the electron:
  - **200x more massive**
  - **Unstable**: decays to $e^-, \bar{\nu}_e, \nu_\mu$
- **2.2 μs lifetime:** easy to make and manipulate at accelerators

- **"Goldilocks" Mass:**
  - Heavier than electron so more sensitive to virtual particles
  - Lighter than pion so no hadronic decays
- Have a property called **spin** that rotates in a magnetic field
- Self-analyzing decay (e.g. muon spin direction at decay links to decay electron direction)

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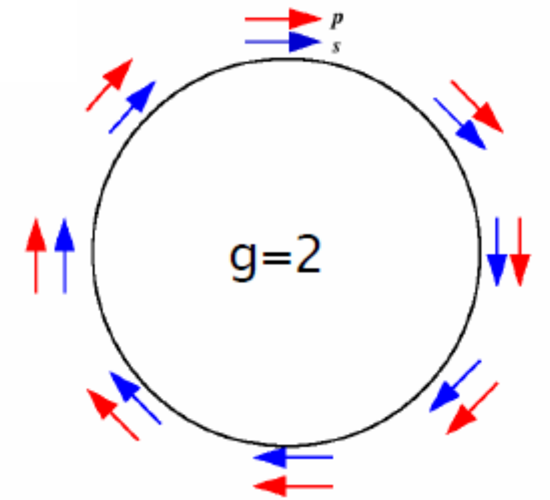
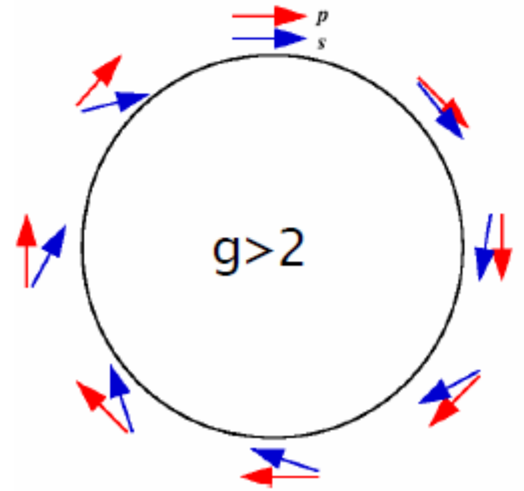
MUONS IN A STORAGE RING (NO E FIELD YET)

- Cyclotron frequency: $$\omega_c = \frac{e}{m\,\gamma} B$$
- Spin precession frequency: $$\omega_S = \frac{e}{m\,\gamma} B\,(1 + \gamma\, a_\mu)$$

Larmor + Thomas precession

$$\boxed{\vec{\omega}_a = \vec{\omega}_S - \vec{\omega}_c = \frac{e}{m}\left(a_\mu\,\vec{B}\,\right)}$$





MUONS IN B AND E FIELD

- In presence of additional E-field (neglecting $\beta \cdot B$ and EDM terms):

$$\vec{\omega}_a = \frac{e}{m}\left(a_\mu \vec{B} - \cancel{\left(a_\mu - \frac{1}{\gamma^2 - 1}\right)}\cancel{\frac{\vec{\beta}\times\vec{E}}{c}}\right)$$

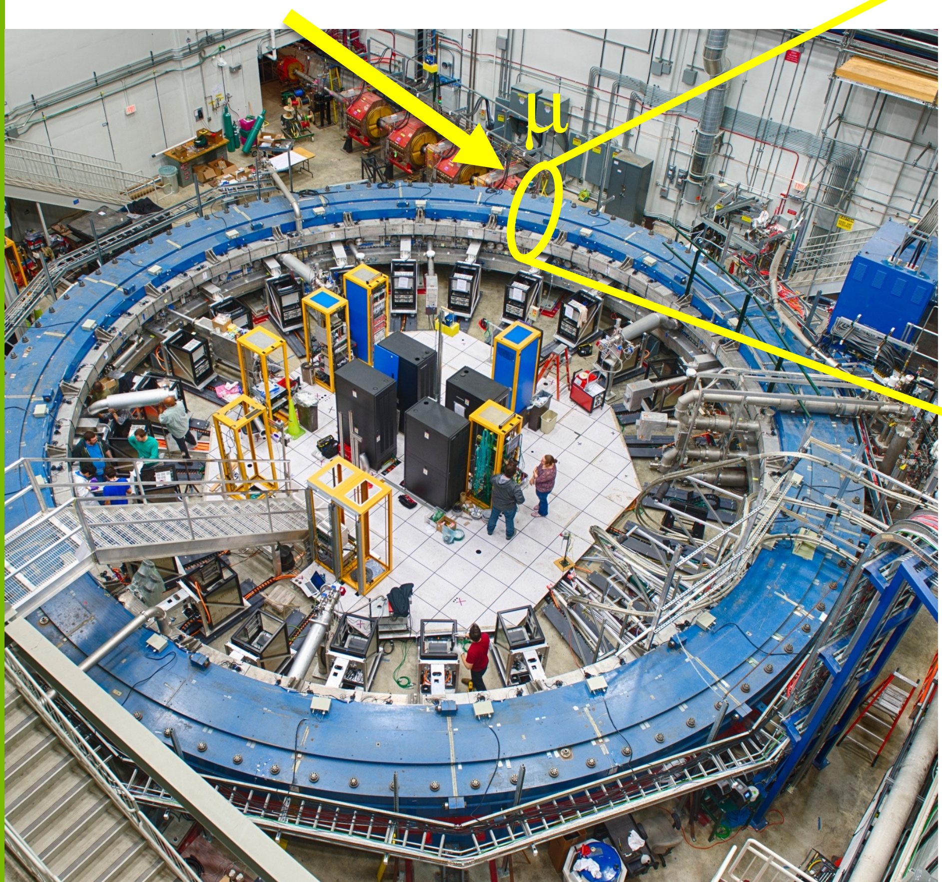
Magic momentum (γ = 29.3, p=3.094 GeV/c)
E field for vertical focusing
CERN-III, BNL E821, Fermilab E989

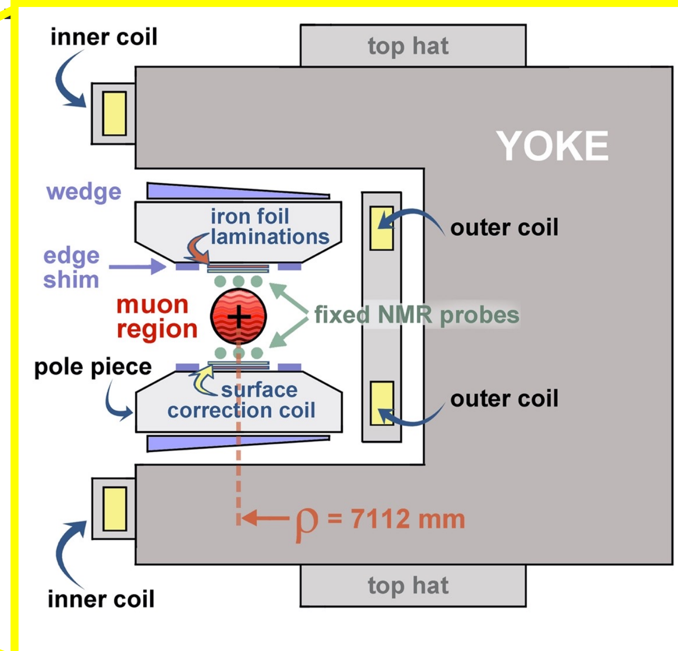
No E field: E = 0
Weak magnetic focusing
J-PARC E34

$$\boxed{\omega_a = e/m\ a_\mu\ B}$$

- Measuring the anomalous moment a_μ requires both
  1. the spin precession frequency ω_a
  2. the magnetic field B

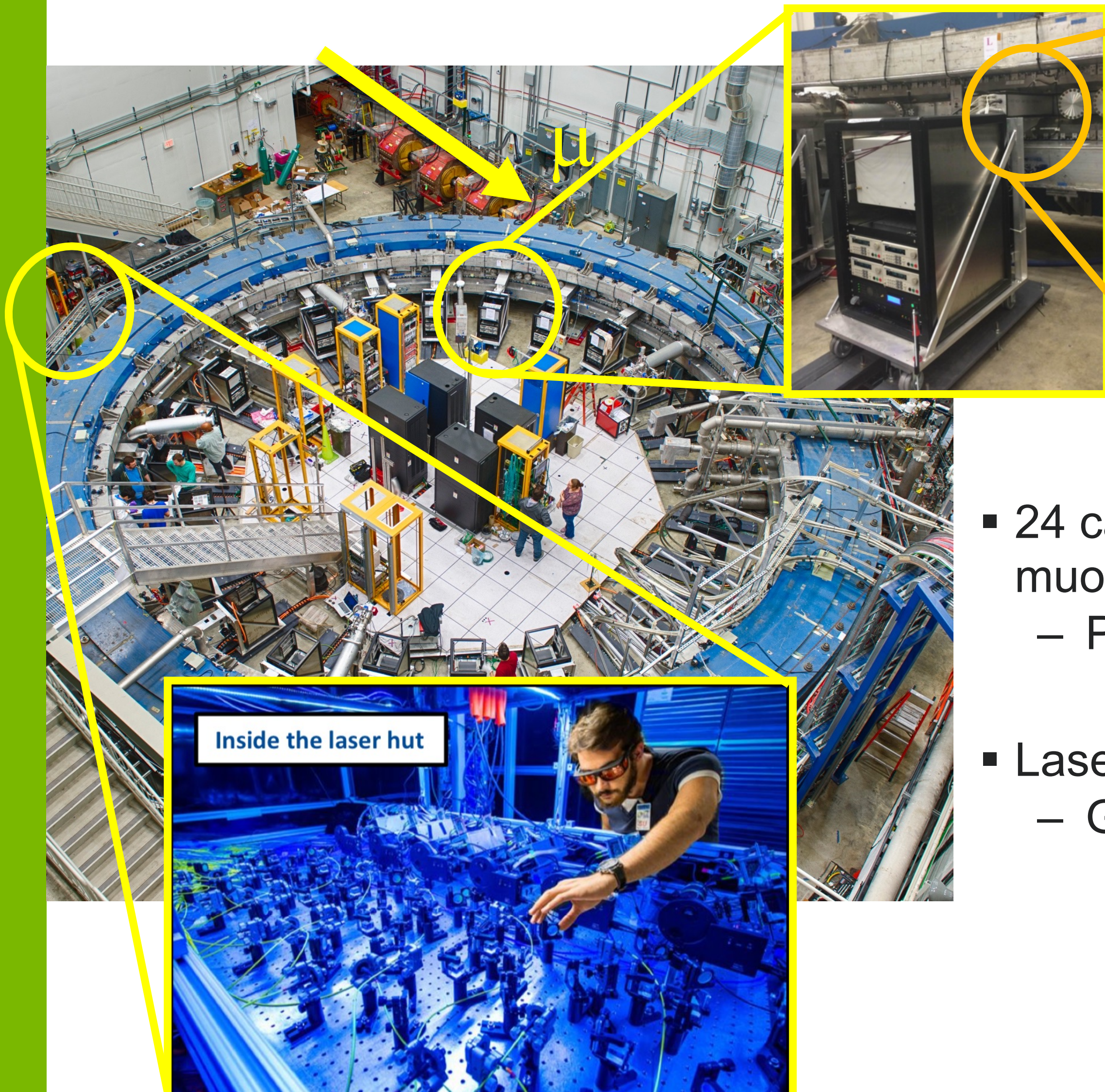
MUON INJECTION & STORAGE: STORAGE RING MAGNET

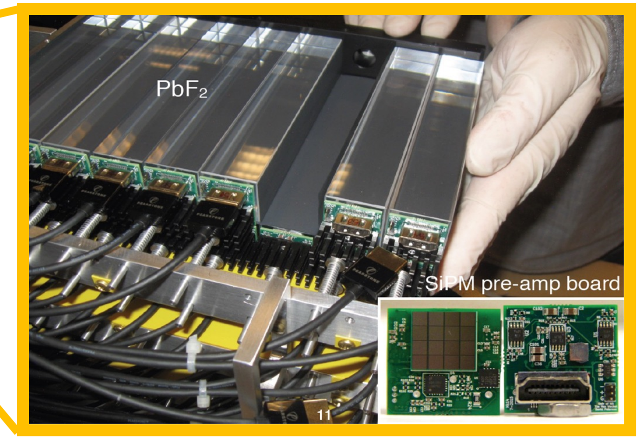




- Superconducting coils, C-shaped yoke, 1.45T field strength
- Shim toolkit:
  - 48 top / bottom hats to tune dipole
  - 800 wedge shims to tune dipole
  - 9000 iron foils to fine tune field
  - 200 tunable coils for higher multipoles

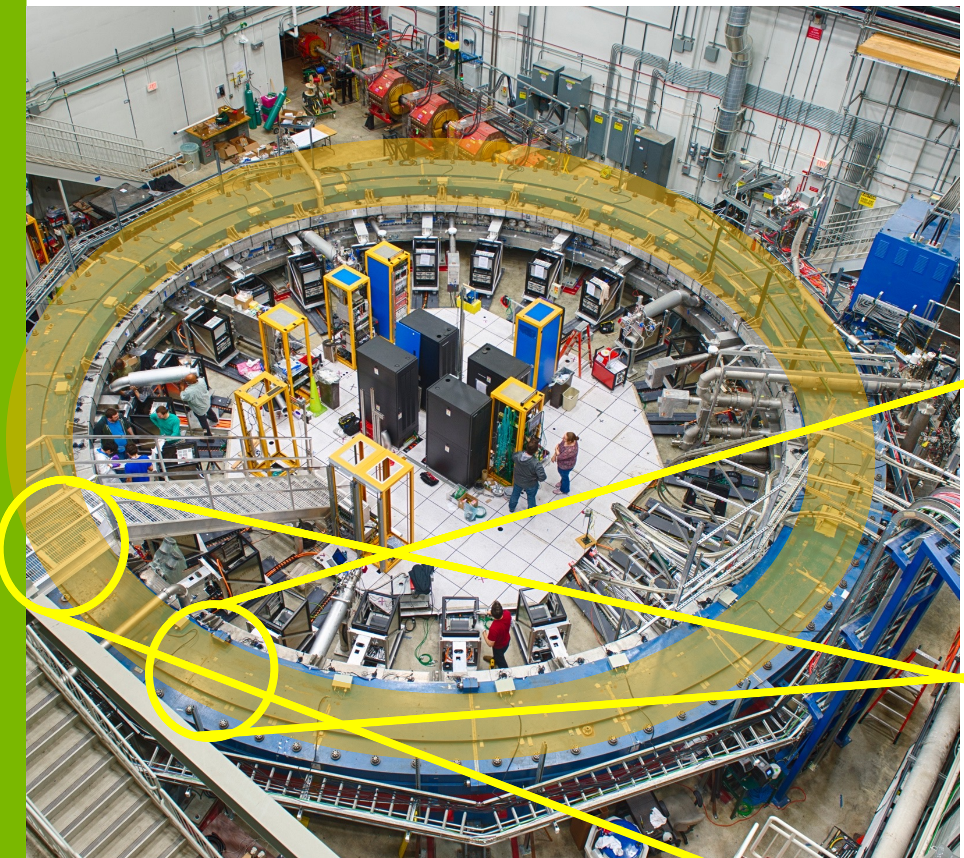
MEASURING THE MUON SPIN PRECESSION: CALORIMETER & LASER CALIBRATION





- 24 calorimeter stations detect the muon decay positrons:
  - PbF_2 crystals with SiPM readout
- Laser calibration system:
  - Gain corrected to 10^{-4}/h

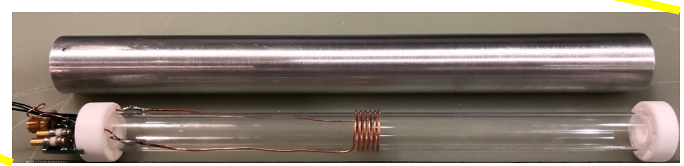
MEASURING THE MAGNETIC FIELD: NUCLEAR MAGNETIC RESONANCE PROBES



- 378 fixed NMR probes to track field

- One trolley with 17 NMR probes to map the field in muon storage region

- Water-based calibration probe to provide an absolute reference



MY PATH TO THE ECA AND LESSONS LEARNED

IT IS THE YEAR 2012: MY FIRST ATTEMPT

- Just started at Argonne as the only staff on Muon g-2
- Muon g-2 Project had tasked me to take on the Slow Control for the experiment
- EC proposal: Slow control for Muon g-2

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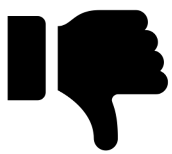

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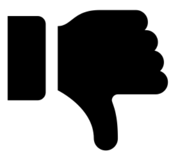

- Review feedback: Nice proposal but…
  – Not really innovative
  – Why wouldn’t the Project pay for it

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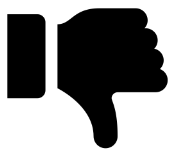

- Review feedback: Nice proposal but…
  - Not really innovative
  - Why wouldn’t the Project pay for it

Lesson 1: Did not know the EC proposal process well and did not have much advice since only one on g-2 at ANL

FAST FORWARD TO 2013: MY 2ND ATTEMPT

- Muon g-2 needed more people for the magnetic field measurement
- I joined and was asked to upgrade the existing, crucial trolley system

- The system is a single point of failure, so I proposed to build a new one for Muon g-2 (while upgrading the old one on Project funds)
- Value proposition: Systematic uncertainty of 70ppb can go to <60ppb

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- Outcome:

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Lesson 2: This time I had a good mentor for proposal writing and I should have listened more that I needed a stronger value proposition

FAST FORWARD TO 2014: MY FINAL ATTEMPT

Analysis (80% of proposal)

- Value gap: Many groups for the ω_a analysis, but no concerted effort for magnetic field
- Proposal focus to form a magnetic field analysis group

- Largest group for field analysis
- Analysis center also due to solenoid test facility

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- New trolley too much scope
- Upgrade existing trolley with enhanced features:
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  - New spherical probes

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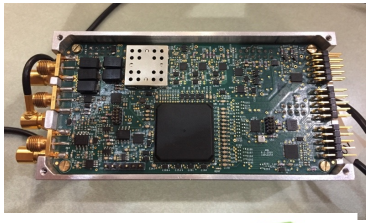
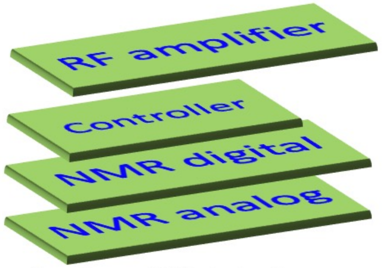
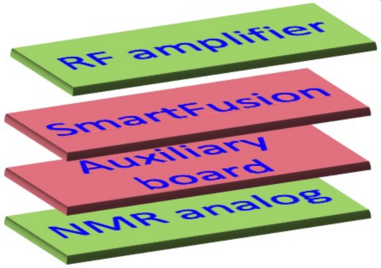




Brookhaven E821 electronics



Fermilab E989 electronics

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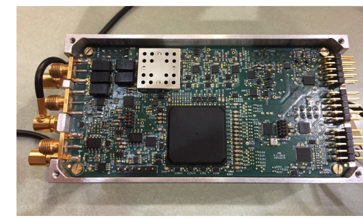

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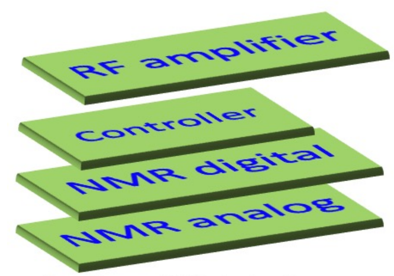

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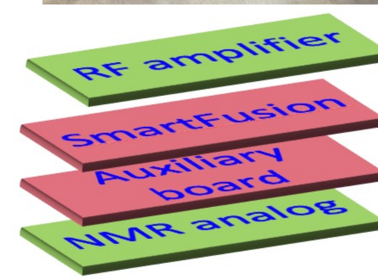

Fermilab E989 electronics

Provide added value

- Explicit table of impact for each activity

Systematic uncertainties for ω_p	E821 [ppb]	E989 goal [ppb]	Added value of proposal: Analysis center	Added value of proposal: New trolley features
Absolute calibration of standard probe	50	35	✓	
Calibration of trolley probes	90	30	✓	✓
Trolley measurement of B_0	50	30	✓	✓
Interpolation with the fixed probes	70	30	✓	✓
Muon distribution	30	10	✓	
Others†	100	30	✓	✓
Time-dependent external fields	-	5	✓	
Total systematic uncertainty ω_p	**170**	**70**		

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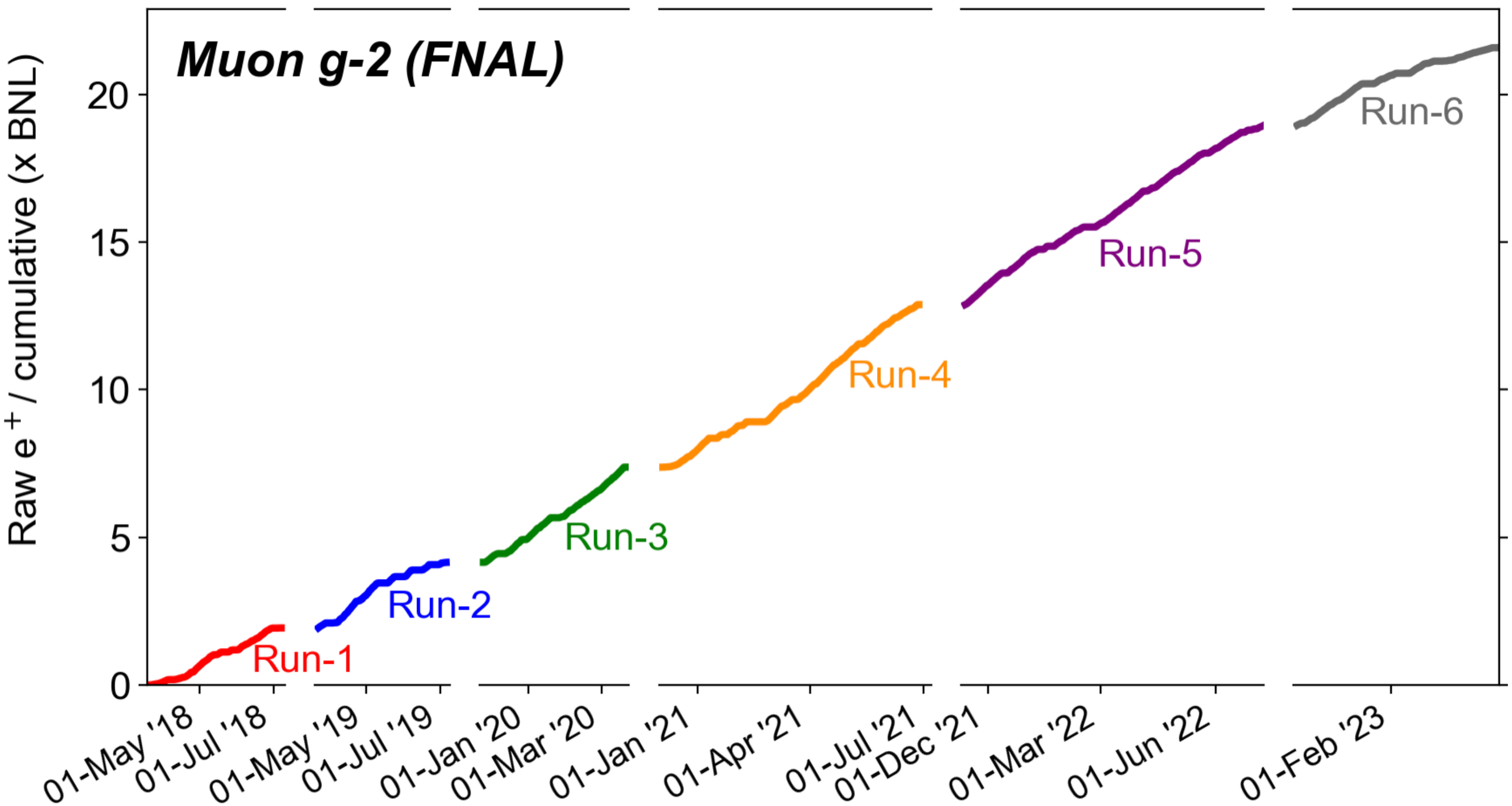
MUON g-2: STATUS AND OUTLOOK

SHORT SUMMARY OF DATA TAKING



- Run-1: First result in 2021 confirmed BNL result with similar precision
- Run-2/Run-3: Second result 2023 with of statistical and systematic uncertainty by each a factor of 2.2
- Run-4/Run-5/Run-6: Final result expected 2025 with precision of <140 ppb

RUN-2/3 UNCERTAINTIES: FINAL VALUES

Quantity	Correction [ppb]	Uncertainty [ppb]
ω_a^m (statistical)	–	201
ω_a^m (systematic)	–	25
C_e	451	32
C_p	170	10
C_{pa}	-27	13
C_{dd}	-15	17
C_{ml}	0	3
$f_{\text{calib}}\langle\omega'_p(\vec{r}) \times M(\vec{r})\rangle$	–	46
B_k	-21	13
B_q	-21	20
$\mu'_p(34.7^\circ)/\mu_e$	–	11
m_μ/m_e	–	22
$g_e/2$	–	0
Total systematic	–	70
Total external parameters	–	25
Totals	622	215

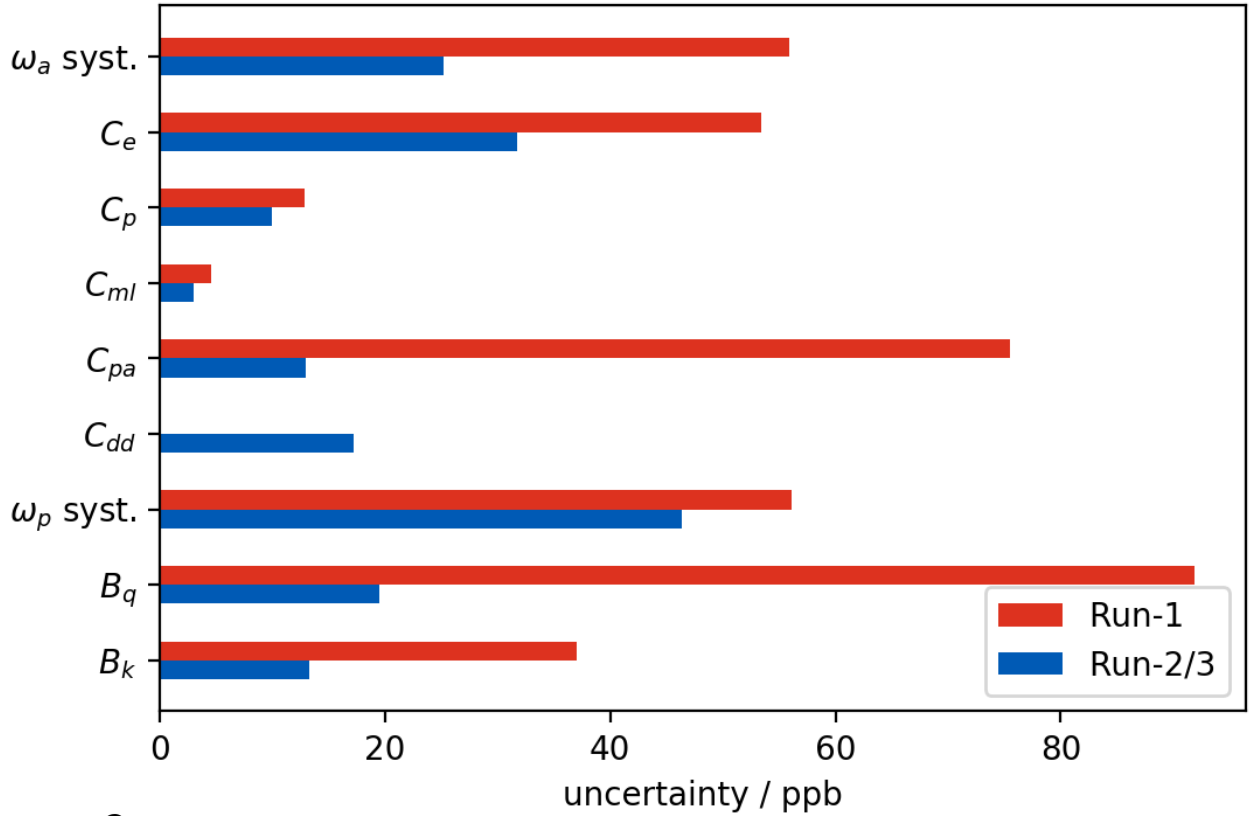
Total uncertainty is **215 ppb**

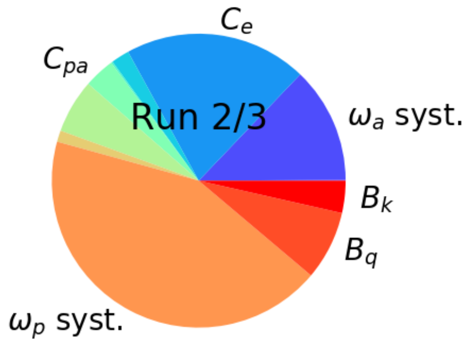
[ppb]	Run-1	Run-2/3	Ratio
Stat.	434	**201**	2.2
Syst.	157	**70**	2.2

- Near-equal improvement: We're still **statistically dominated**

Systematic uncertainty of 70 ppb surpasses our proposal goal of 100 ppb!

RUN-2/3 UNCERTAINTIES: IMPROVEMENT IN ALL PARAMETERS

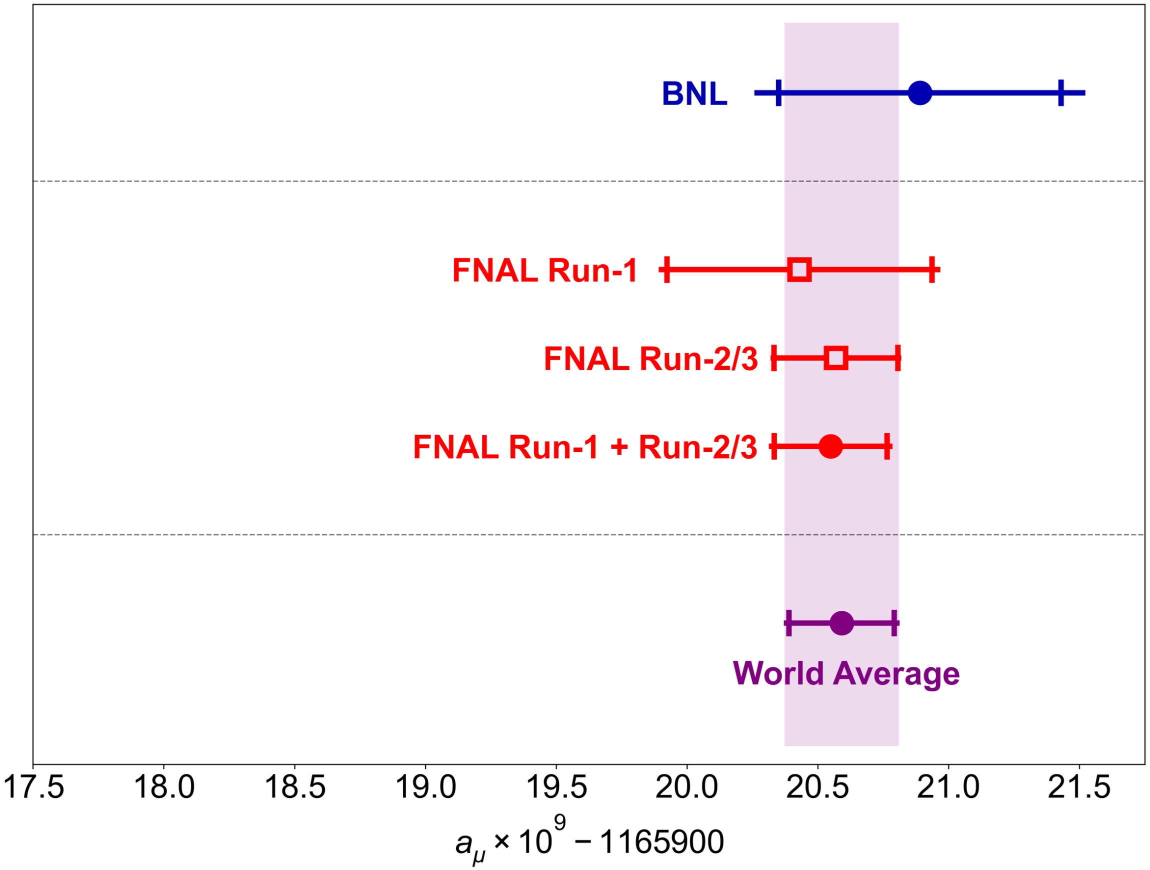




- After improvements, total systematic comes from **multiple sources**

RUN-2/3 RESULT: FNAL + BNL COMBINATION

a_μ(FNAL) = 0.00 116 592 055(24) [203 ppb]

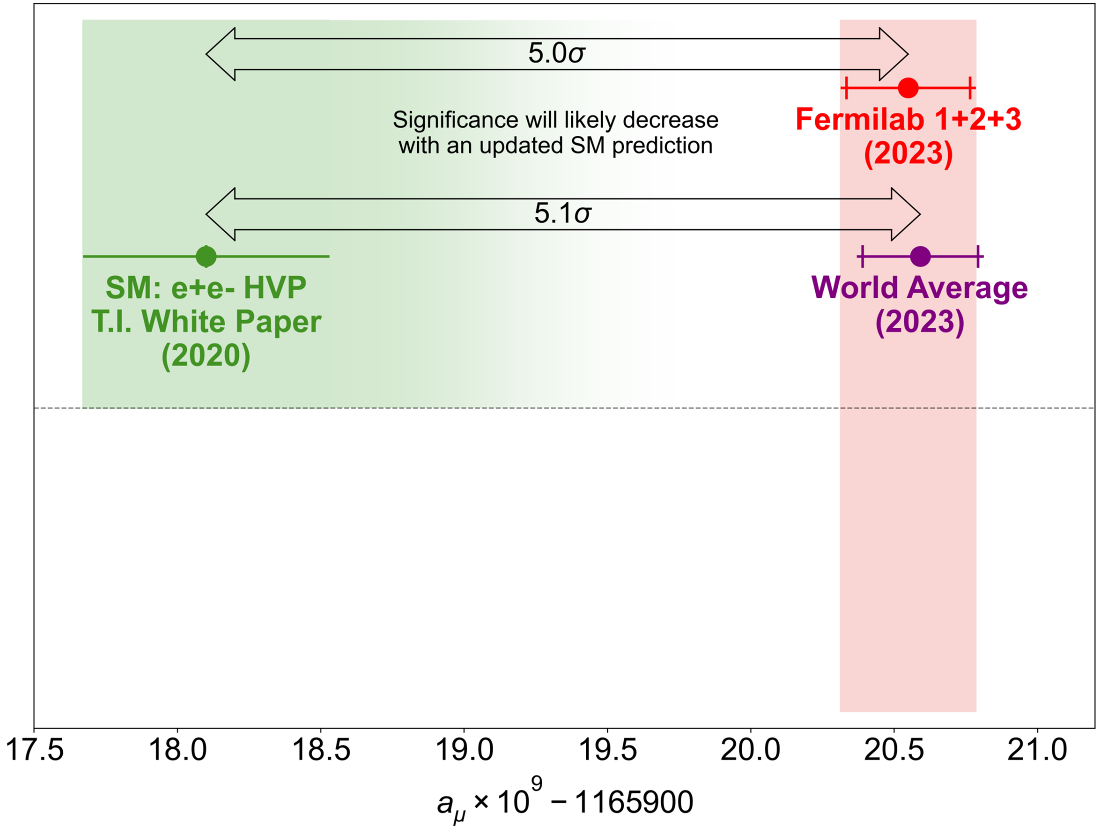


- FNAL combination: **203 ppb** uncertainty
- Both FNAL and BNL dominated by statistical error
- Combined world average **dominated by FNAL** values.

a_μ(Exp) = 0.00 116 592 059(22) [190 ppb]

EXPERIMENT VS THEORY COMPARISON

Theory prediction is less clear now, but we can still compare



Large discrepancy between experiment and WP (2020)

Significance for **Fermilab alone** get to **5.0σ**

Updated prediction considering all available data will likely yield a smaller and less significant discrepancy

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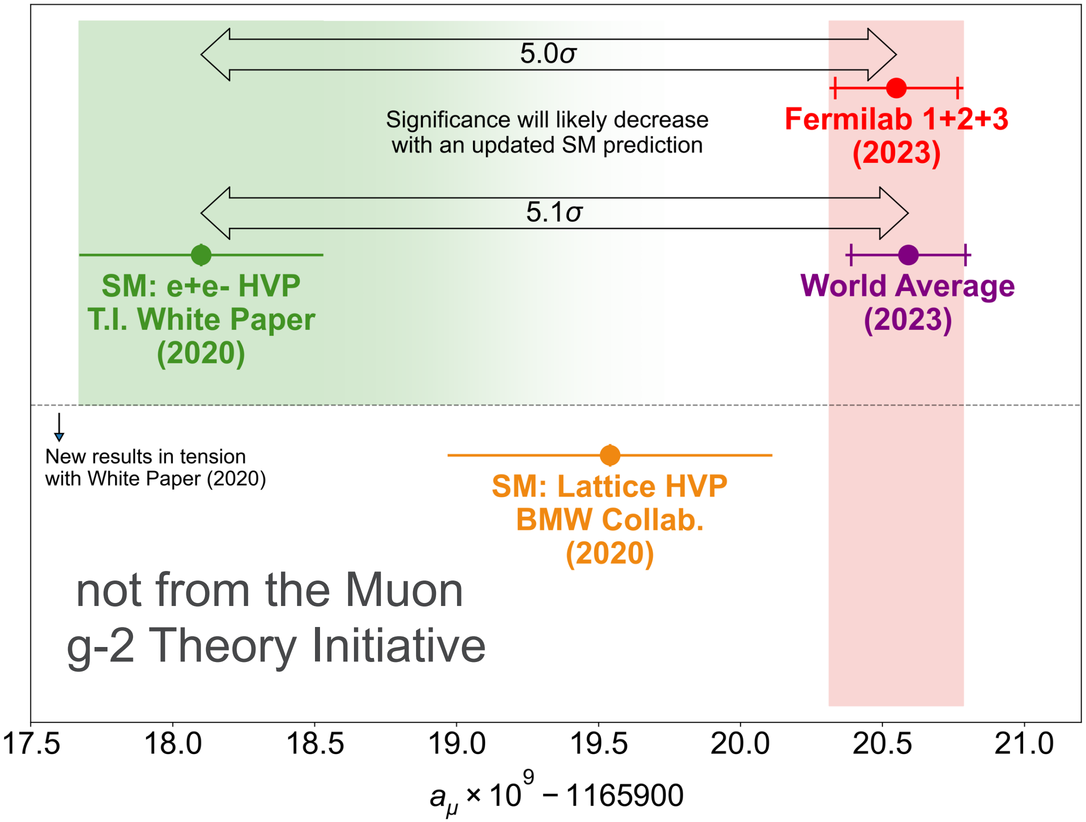


Include **BMW** result by swapping HVP from WP with their value

Note: BMW is currently the only full lattice calculation of HVP

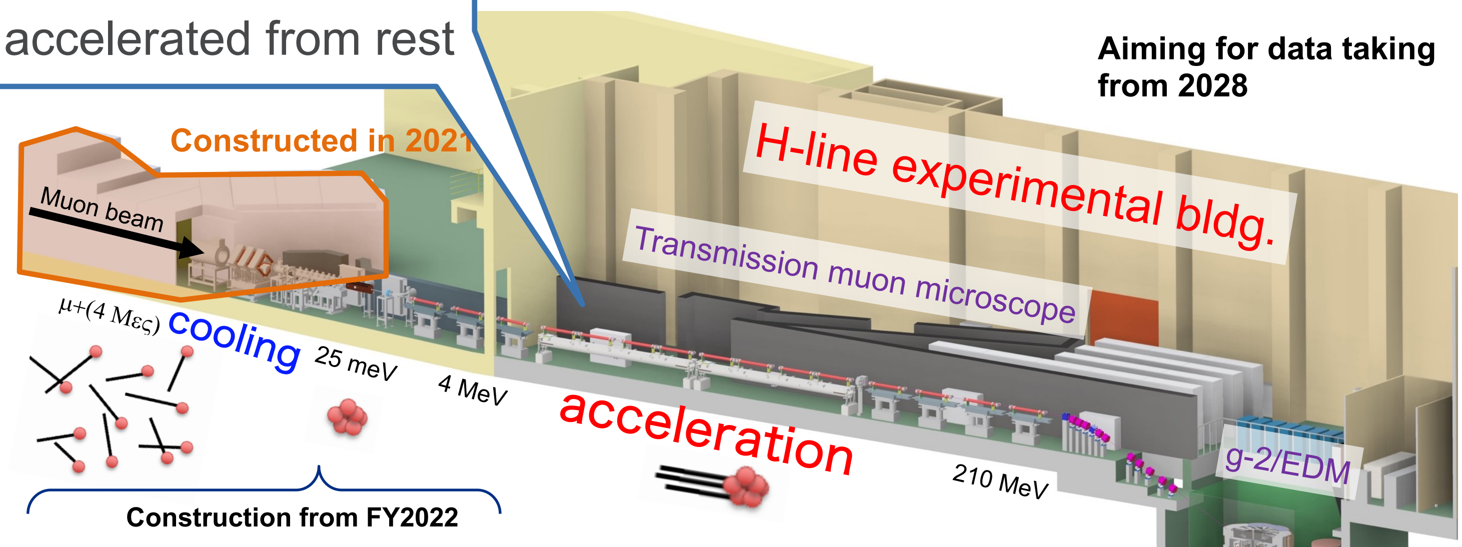
INTENSITY FRONTIER:

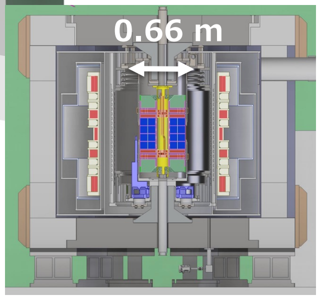
MY VERY PERSONAL VIEW ON NEW OPPORTUNITIES

J-PARC MUON g-2/EDM EXPERIMENT

Muons accelerated from rest

Aiming for data taking from 2028





Smaller magnet, no E-field -> complementary technique

$$\vec{\omega}_a = -\frac{q}{m}\left(a_\mu \vec{B} - a_\mu \frac{\gamma}{\gamma+1}\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta} + \cancel{\left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}x\vec{E}}{c}}\right)$$

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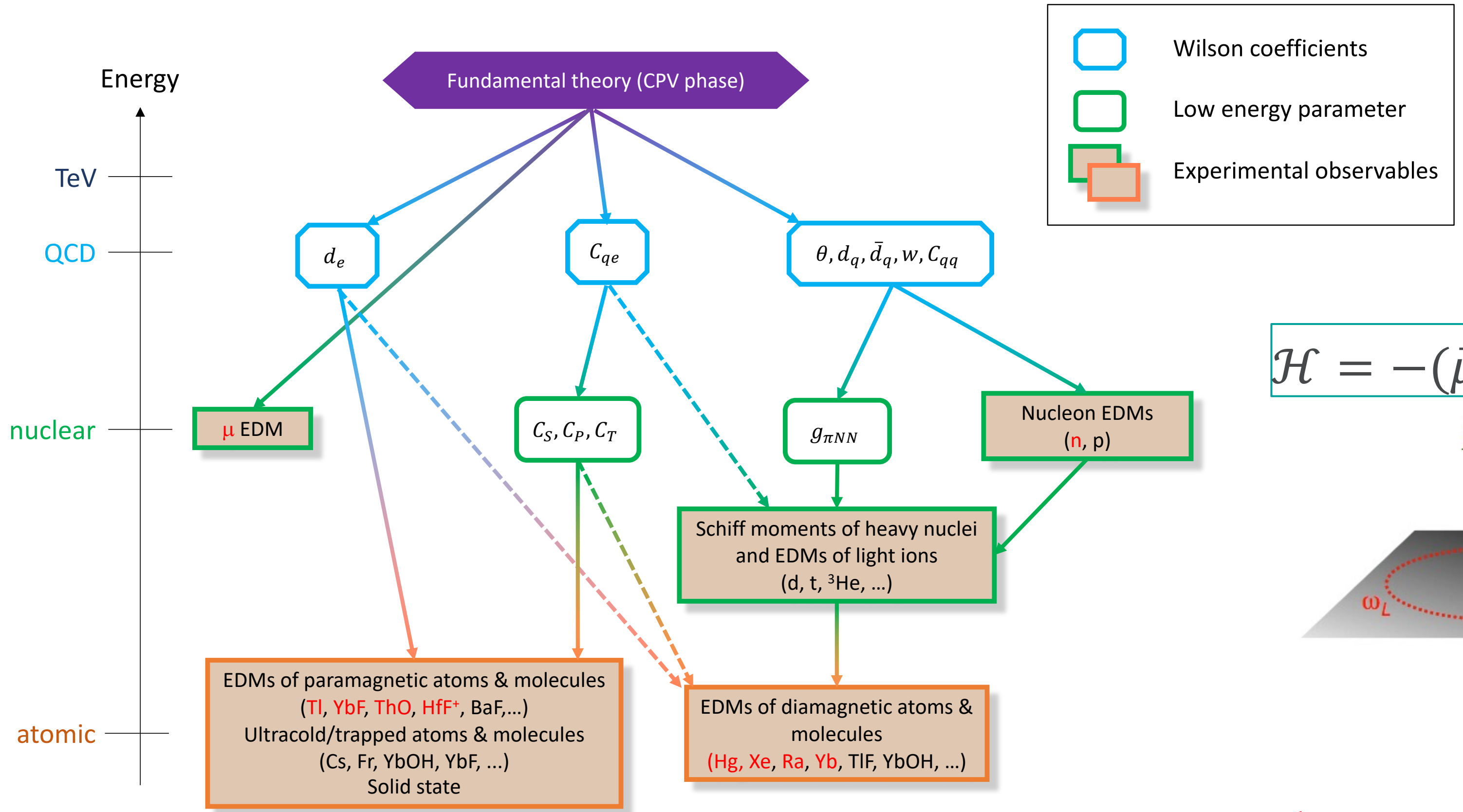
INTENSITY FRONTIER: MUCH OF THE PROGRAM FOR THE NEXT DECADE IS CLEAR

Flavor physics is a central focus: Mu2e, LHCb, Belle-II

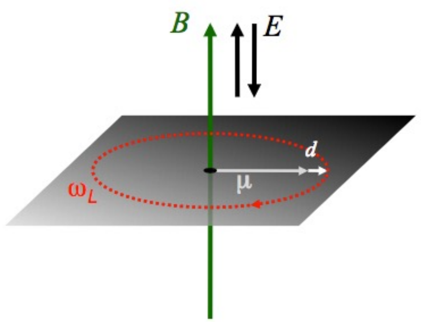
- Frontier suggested in Snowmass report to add another science driver *“flavor as a tool for discovery”*
  - Understand flavor families and their (different) properties
  - Study flavor-specific decays to search for new physics
- Continued support for LHCb and Belle-II
- CLFV experiments with muons (especially Mu2e and Mu2e-II) are important components to the program
- Select portfolio accelerator-based dark sector experiments
- …

ELECTRIC DIPOLE MOMENTS

EDM searches will play an important role to search for BSM physics



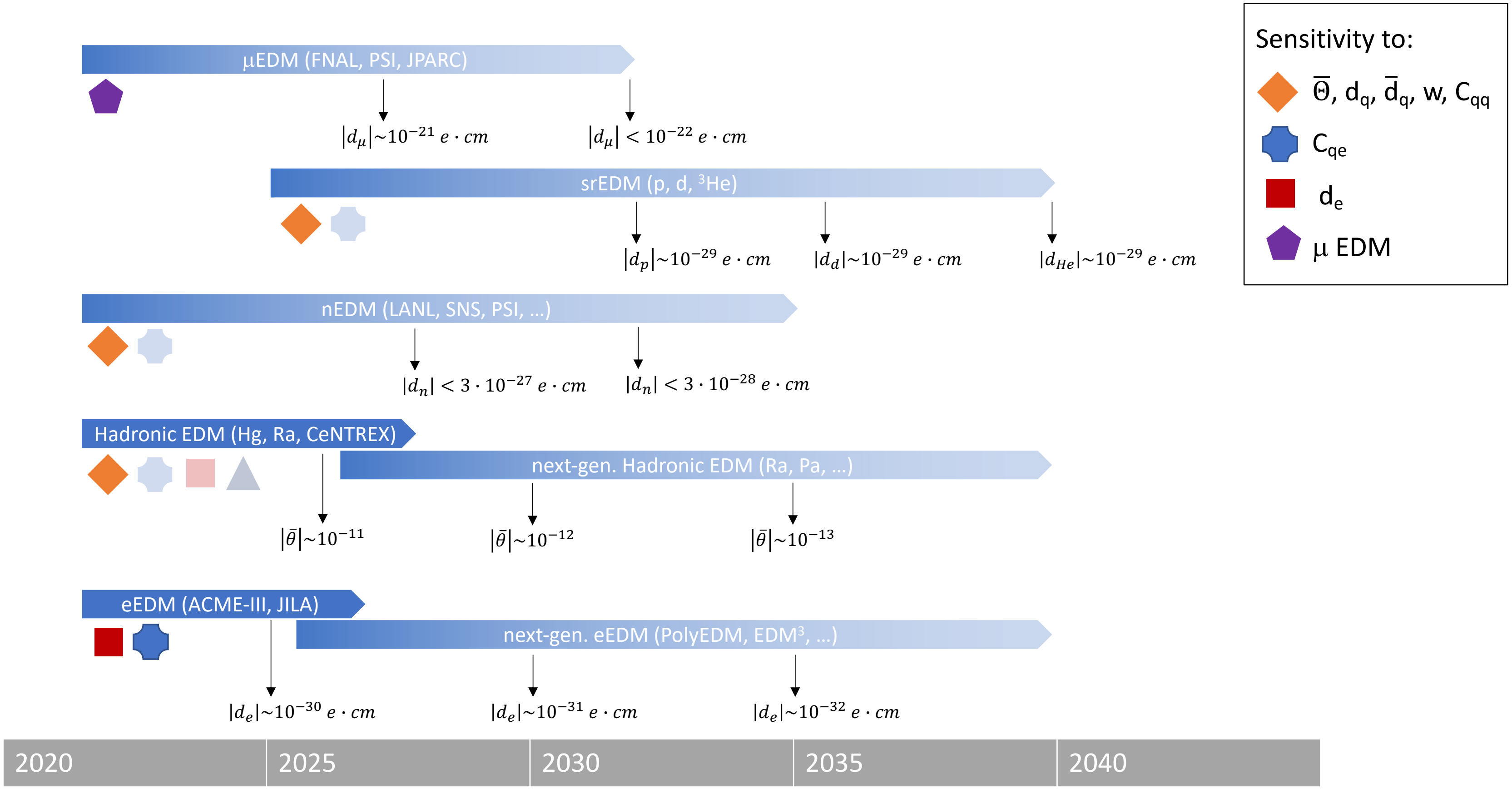
$$\mathcal{H} = -(\vec{\mu} \cdot \vec{B} + \vec{d} \cdot \vec{E})$$



$$\Delta\omega(E\uparrow - E\downarrow) = \frac{4dE}{\hbar}$$

- Complementary EDM searches in AMO, NP, and HEP are needed to disentangle nature of underlying CP violation

NEW OPPORTUNITY: STORAGE RING EDM



- Different communities (AMO, NP, HEP) can benefit and exploit synergie:
  - srEDMs can learn from years of experience with table top EDM searches
  - As AMO/NP EDM searches grow, there collaborations grow posing new challenges
  - Detector systems can be used in various ways (e.g. quantum sensors, interferometeres, …)